Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

DIVISION OF INFORMATION FILE COPY

UNITED STATES DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE

WIND-TUNNEL STUDIES OF FUNDAMENTAL PROBLEMS RELATED TO WINDBREAKS

By

N. P. Woodruff, Agricultural Engineer

and

A. W. Zingg, Project Supervisor

Soil Conservation Service - Research

U. S. DEPT. OF AGRICULTURE
NATIONAL AGRICULTURAL LIBRARY

MAY 16 1969

CURRENT SERIAL RECORDS

In cooperation with the Kansas Agricultural Experiment Station

SCS-TP-112

Washington 25, D. C.

August 1952

WIND-TUNNEL STUDIES OF FUNDAMENTAL PROBLEMS RELATED TO WINDBREAKS[1]

By N. P. Woodruff, agricultural engineer, and A. W. Zingg, project supervisor, Soil Conservation Service--Research

CONTENTS

	Page
Review of previous work	2
Scope and general methods of study	3
Results of the study	5
Similarity of flow patterns	5
Reduction in average horizontal velocity	10
Streamlines of flow over the objects	12
Force and velocity on the surface to the lee of the objects	15
Extension of results to atmospheric conditions	19
Discussion	22
Summary	23
Literature cited	24

Surface barriers placed normal to the winds have been widely used to protect crops and lands from the ravages of wind. Interest in the use of windbreaks for this purpose in the High Plains of the United States reached a peak with the shelterbelt program of the 1930's.

Very little research has been conducted on the effect of barriers on the wind and on their protective influences since the shelterbelt program was terminated in 1942. Much of the research work in the past has been sporadic and has led to variable or conflicting results. Field research with the actual phenomena is handicapped by the difficulty of obtaining control over the variables encountered. Furthermore, obtaining data throughout the zone of influence of a full-scale shelterbelt is a tremendous physical task.

It is the purpose of this research to study rather completely the principles involved in the placement of barriers or windbreaks through the use of a wind tunnel and small-scale models.

Investigations in the fields of meteorology, hydraulics, and aerodynamics have shown that a frictional drag is developed when a fluid such as air in a wind tunnel, water in either open or closed conduits, or atmospheric wind flows over a boundary surface. Placing obstacles, such as windbreaks, in the path of the wind creates a new boundary surface of separation at an elevation approximately equal to the height of the obstacle. This lessens the drag on the original surface and lowers the prevailing surface velocity. Considered from the standpoint of wind-erosion control, benefits may accrue wherever the direct force of the wind on the soil is decreased.

---

[1]Contribution from the Department of Agronomy, Kansas Agricultural Experiment Station, Manhattan, Kans., and the Soil Conservation Service, U. S. Department of Agriculture. Cooperative investigations in the mechanics of wind erosion.

The effectiveness of an obstacle in creating a new boundary and lowering the surface velocity depends upon the object's shape, height, and density and upon the velocity of the wind. The evaluation of the individual effect of these variables has not been solved completely.

More information is needed on the extent of the lag of the wind velocity within the influence of an obstacle. This lag will extend to the limits of the new boundary surface. When these limits are reached the air responds to the pull of the faster moving currents and regains its initial velocity. Just how far these limits extend is problematic.

This paper presents results of studies designed to obtain information on some of the preceding problems. The scope of the report is limited to the investigations and results of studies on single barriers having variable geometrical shapes.

REVIEW OF PREVIOUS WORK

The amount of material published on the subject of windbreaks is voluminous. Much of the research has dealt with cultural aspects of the problem; i. e., species, planting, management, and care of plants. Since 1936, a number of field investigations and one wind-tunnel study have been conducted to find answers to some of the aerodynamic problems related to windbreaks. This review of literature is limited to some of the reports which present scientific data on the effectiveness of windbreaks.

Between 1935 and 1938 the United States Forest Service conducted a number of studies to define more clearly the influence of shelterbelts. Much of this work was implemented by C. G. Bates (3, 4, 5).[2] The studies were conducted at Huron, S. Dak., and at Holdrege, Nebr. The studies at Huron were devoted to evaluating the influence of windbreaks on agronomic features and practices; i. e., reducing wind velocities over field crops, retention of moisture, and effect on crop yields. The studies at Holdrege were conducted to evaluate the effect of windbreaks on house heating. Slat-fence barriers were used in lieu of actual windbreaks on both of these projects.

In 1936 DenUyl (9) of the Forestry Department of the Purdue Agricultural Experiment Station conducted field tests of actual windbreaks in Indiana. His data included records of temperature, humidity, and wind velocity over a period of 5 years. He used five natural windbreaks of different density and species in his studies. The scope of the results was somewhat limited due to the influences of buildings near the windbreaks.

The Regional Forestry Division of the Soil Conservation Service published, in 1947, a pamphlet entitled "Tree Windbreaks for the Southern Plains" (25). This report includes information on the effects on wind movement, adaptability of trees for the Southern Plains, planting, management, arrangement, and care.

Others who have worked on the problem in the United States are: Cheyney (7) of the Minnesota Agricultural Experiment Station who obtained data on wind-velocity reduction and the effect of drafts or openings in the breaks; George (11), information on spacing within breaks; Staeckler (23), recommendations on the number of rows within breaks and replacement of trees; Hood (14), data on distance of protection to lee and effect on crop yield; Clark (8) and Trenk (24), data on wind-velocity reduction.

Although windbreaks have been used by Chinese farmers for many years (6), there

[2] Figures in parentheses refer to Literature Cited at end of publication.

does not seem to be evidence of any researches on their value. Workers in Russia (12, 15, 22, 26), Sweden (2), Denmark (10), Australia (1), and Canada (13, 18, 27) have also reported findings relative to windbreaks. Of this group, Russian workers have published the most data on the subject; however, their data contain no discussion of methods used, thus making it difficult to evaluate published results. There appears to be considerable difference of opinion among Russian workers in regard to the spacing and effectiveness of windbreaks. DenUyl (9) presents a rather complete list and discussion of the various foreign publications.

A wind-tunnel study of windbreaks was conducted by J. S. Atsumi in 1936 at the California Institute of Technology. Results of his work are included in a paper by Malina (16). Atsumi used 1-inch cotton balls as model trees. He had 11 tree arrangements, ranging from a single row up to 6 rows spaced in different echelons. His results demonstrated that the shielding effectiveness per tree was greatest for a single row of trees. It was concluded, however, that 2 rows spaced 1 tree-height apart and 1 tree-height wide gave much better protection per windbreak.

A recent review of published literature on windbreaks is given in an excellent master's thesis report by W. N. Moreland (17). Sixty-three references, both foreign and domestic, are listed and discussed.

SCOPE AND GENERAL METHODS OF STUDY

The fundamental problems related to windbreaks which are evaluated in this study are: (1) effect of barrier shape on flow patterns, (2) effect of different velocities about a barrier of constant shape; i. e., the differences in flow with different velocities, (3) the determination of the zone of influence of barriers of different shape, and (4) evaluation of wind-tunnel results in terms of atmospheric conditions.

The study of these problems was carried out in a wind tunnel which has been described by Zingg and Chepil (30). The working section used for this particular experiment consisted of a 9-foot horizontal length beginning at a point 40 feet downwind from the fan. The top of the tunnel for this section was constructed to facilitate horizontal movement of a staff of Pitot tubes through the entire 9-foot length. The floor of the tunnel consisted of gravel of a size-range $>1/6$ and $<1/4$ inch. This gave a rough surface resulting in the development of a turbulent boundary layer several inches deep at the 42-foot point.

The four objects used in the wind-tunnel experiments were a thin-edged vertical plate, a cylinder, a 45° triangular shape, and a model tree windbreak. The cylinder and triangular shapes were constructed from galvanized sheet metal. The material used for the vertical plate was 1/16-inch aluminum sheeting. The model windbreak was constructed from cedar boughs mounted on 2 by 2-inch blocks of wood. Spacing between the trees was 1.5 inches. The corresponding spacing for 30-foot trees would be 11.25 feet. The windbreak was placed in the tunnel as shown in figure 1, page 4. All the objects were 4 inches high and 36 inches long. They were placed horizontally on the floor of the tunnel perpendicular to its axis at the 42-foot point, which was designated as station 0. The flow of air about each of the objects was studied through use of horizontal velocity measurements, streamlines of flow, pressure readings, and shear patterns on an erodible sand surface to the lee of the object. Use was also made of intensity-frequency estimates of winds in integrating the results to atmospheric conditions.

Horizontal velocity measurements were taken with a rack of four Pitot tubes and an alcohol manometer. The Pitot tubes were mounted on a staff gage with a vernier scale to facilitate accurate and rapid vertical movement.

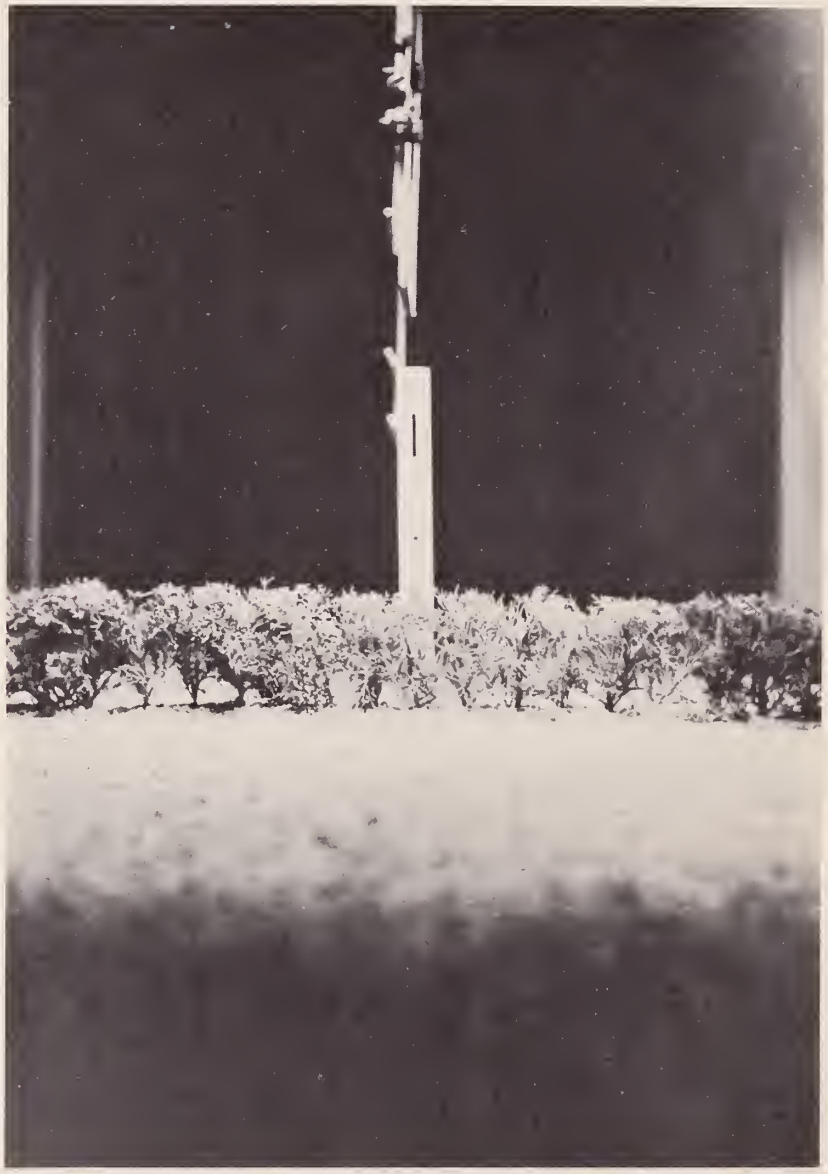

FIGURE 1.--Model trees oriented in wind tunnel.

Streamlines of flow were made by sketching the paths of illuminated particles. Aluminum powder was introduced into the airstream of the wind tunnel and made visible by the use of a light-concentrating system (29).

Pressure readings were made by use of Ellison draft gages.

Areas of protection were delineated through the use of an erodible sand. The threshold velocity or force required to erode the sand in the clear tunnel was first determined. The sand was then placed in the lee of the objects. A wind of velocity greater than the threshold was passed over the object and sand. The boundary of the sand pattern remaining at the end of the test denoted the location of the threshold velocity or force. The sand was cleared off the floor by greater velocity and force beyond this boundary limit.

RESULTS OF THE STUDY

The results obtained from the preceding methods of study are discussed under the following five general headings: (1) Similarity of flow patterns, (2) reductions in average horizontal velocity, (3) streamlines of flow over the objects, (4) forces and velocities on the surface to the lee of the objects, and (5) extension of the results to atmospheric conditions.

Similarity of Flow Patterns

The resistance encountered by an immersed body is dependent in part upon boundary shear and in part upon separation and the consequent formation of a turbulent wake. The relative extent to which each of these will affect the flow varies with the Reynolds number characterizing the motion and with the geometrical form and orientation of the body.

Von Kårmån and Nikuradse, as reported by Rouse, (19, p. 248), in carrying out experiments using uniform artificial roughness in pipes, found that if the roughness is of sufficient magnitude and the Reynolds number of flow is high enough the drag coefficient will be independent of the Reynolds number.

Immersing an isolated body in the flow presents a slightly different problem. The problem is further complicated if the body is placed in an already existing turbulent boundary layer. It is possible, however, to prove that at sufficiently high Reynolds numbers the drag coefficient in this case is also independent of the Reynolds number. This may be done by using the analogy between the drag of immersed bodies and the resistance to motion in non-uniform conduits such as venturi meters and plate orifices. Development of these relationships for water along with references to Johansen's work is given by Rouse (19, p. 256) and by Russell (21). Briefly, the development proceeds from use of (a) the mean energy equation for flow between a section in the approach and a section of maximum jet contraction in the conduit, and (b) the continuity equation which gives the standard orifice equation for flow. This equation for a compressible fluid such as air is:

$$G = \frac{Y\, C_d\, a\, w_1}{\sqrt{1 - \left(\frac{a}{A}\right)^2}} \quad 2g\left(\frac{P_1 - P_2}{w_1}\right) \tag{1}$$

where G = *weight rate of air flow in lbs. per sec., or by continuity equation* = $V_1 A_1 w_1$

Y = *expansion factor accounting for expansion of gas as it passes from section 1 in approach to section 2 in contraction*

C_d = *coefficient of discharge*

a = *area of contracted area, sq. ft.*

w_1 = *specific weight of air, lbs. per cu. ft.*

A = *area of approach, sq. ft.*

g = *acceleration of gravity, 32.2 ft. per sec.*^{2}

P_1 = *pressure in approach, lbs. per sq. ft.*

P_2 = *pressure in contracted section, lbs. per sq. ft.*

Both theory and experimental results have indicated that C_d is a function of the Reynolds number for any given ratio of $\frac{a}{A}$. A plot of C_d versus the Reynolds number will show that, for Reynolds numbers low enough for laminar flow, an increase in R will produce a rise in C_d. However, as soon as R becomes large enough for the effect of separation to become noticeable, the upward trend in C_d is gradually offset by the jet contraction. The jet contraction for any given ratio of $\frac{a}{A}$ increases further with increasing turbulence and the curves begin to straighten out and become asymptotic. The discharge coefficient then becomes nearly constant and is independent of the Reynolds number of flow.

The preceding theory is developed for orifices; however, it is also applicable to immersed bodies. This is particularly true in the case of the experiments conducted in this study. Here the position of the object, on the floor of the tunnel, creates a condition similar to that of a single-edged orifice. Carrying this reasoning further and using the usual premise which considers the discharge coefficient to be a reciprocal function of the orifice drag coefficient, it can be demonstrated that the latter is also independent of the Reynolds number.

Figure 2, page 7, shows the results of an experiment designed to demonstrate the applicability of the above theory. Data for the curves were obtained by running a series of tests. Conditions were regulated so that the range of Reynolds numbers of flow was from 7,650 to 514,000. A value of $\frac{a}{A} = 0.89$ corresponds to the ratio present in the tunnel when the objects were in position. Pressure and velocity readings obtained experimentally were used in the orifice equation for a compressible fluid (equation 1) to calculate values of the discharge coefficient C_d.

The discharge coefficient curve shows that the coefficient is independent of the Reynolds number for values of $R > 25{,}000$. The initial part of the curve indicates that

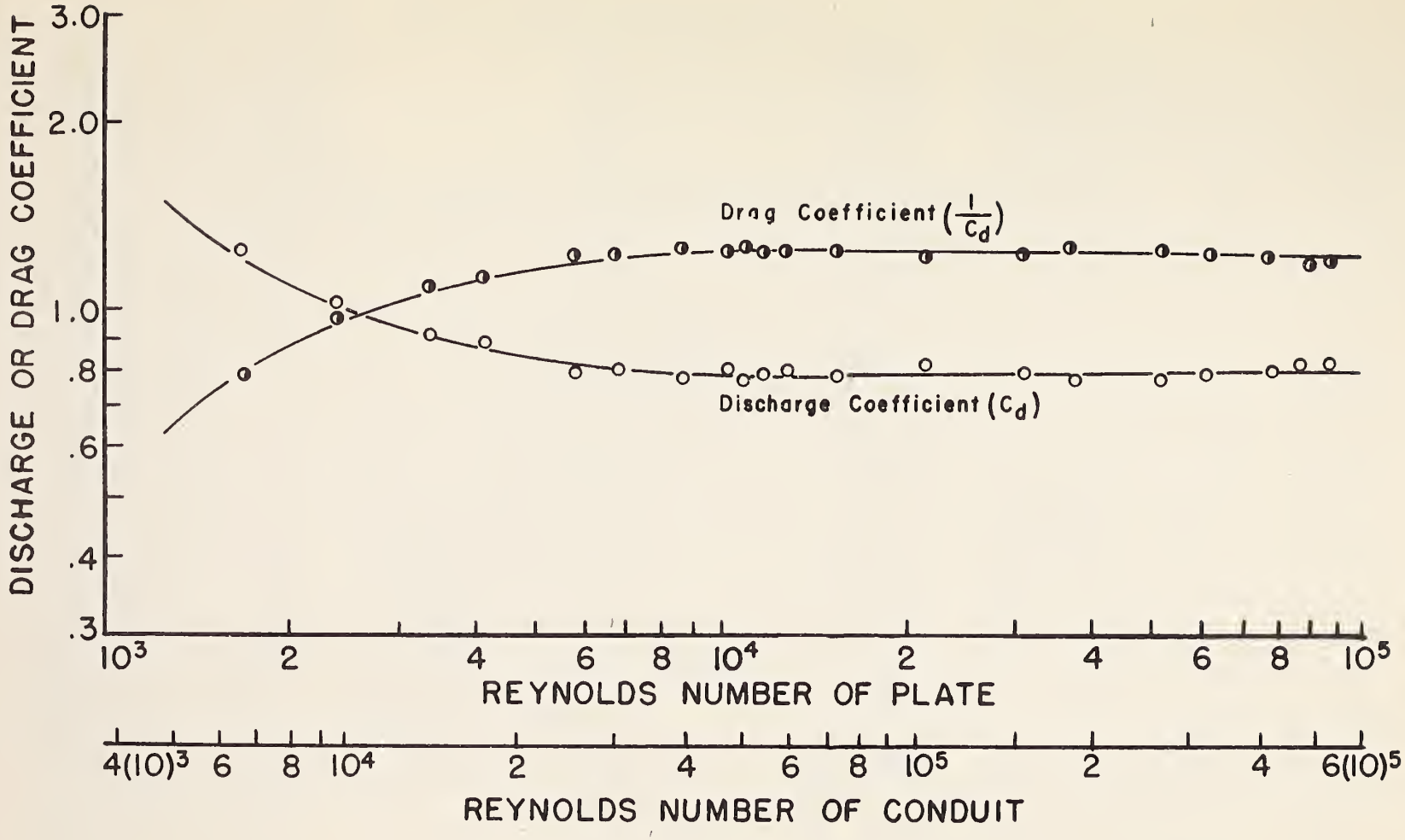

FIGURE 2.--Values of the discharge and drag coefficients in relation to the Reynolds number of the conduit and plate.

separation is occurring and the upward trend is being offset by the jet contraction. This effect continues until an R value of 25,000 is reached and the curve becomes asymptotic to a value of $C_d = 1.3$. The curve corresponds closely to curves shown by Rouse (19, p. 261) for the range of Reynolds numbers involved.

The second curve of figure 2, page 7, shows the reciprocal values of C_d plotted versus the Reynolds number. If the drag coefficient is considered to be equal to this reciprocal then it is also independent of the Reynolds number for values of $R > 25{,}000$. Rouse states that practically every immersed body has its counterpart in a similar conduit transition. He further compares the flow at an abrupt contraction to the flow about a blunt cylinder. If a comparison is made on that basis it is found that the curve for the drag coefficient given in figure 2 corresponds closely both in shape and values to that found by Wieselsberg for smooth cylinders. This curve is also employed by Rouse (20). Certain distinctions exist between flow in a conduit and flow about an immersed body. Further it is realized that the range of Reynolds numbers is relatively small; however, it is believed that, within the range used, the results are a good representation of existing conditions.

The inference from the above experimental results is that similar flow patterns will be obtained about a given object if the flow is characterized by a sufficiently large Reynolds number. This premise was tested by subjecting the 4-inch vertical plate to three flow velocities. The velocities at the 4-inch elevation and the corresponding Reynolds numbers were as follows:

u	R
Ft./sec.	
24.8	$5.12(10^4)$
37.1	$7.65(10^4)$
43.4	$8.95(10^4)$

Horizontal velocity measurements were made at 12 heights at 21 locations in the flow. The data thus obtained were analyzed and tested for similarity by plotting velocity-profile maps using the dimensionless ratios $\frac{z}{H}$ and $\frac{U_p}{U_c}$, where

z = *elevation above datum*
H = *height of the plate*
U_p = *velocity in tunnel with plate*
U_c = *velocity at corresponding point in clear tunnel*

These profiles are shown in **figure 3,** page 9. Marked similarity of flow for the three velocities was obtained. This is a further indication of the independence of the flow pattern to the Reynolds number characterizing the flow.

It is evident that the ratio of the velocities $\frac{U_p}{U_c}$ approaches a constant irrespective of the flow velocity. Percent reduction in velocity is equal to 100 minus the ratio of velocities expressed as a percent. It follows that the percent reduction in velocity attributable to placement of a barrier is also a constant at a given location irrespective of the velocity. Complete protection or benefit must be based on a reduction of velocity to a

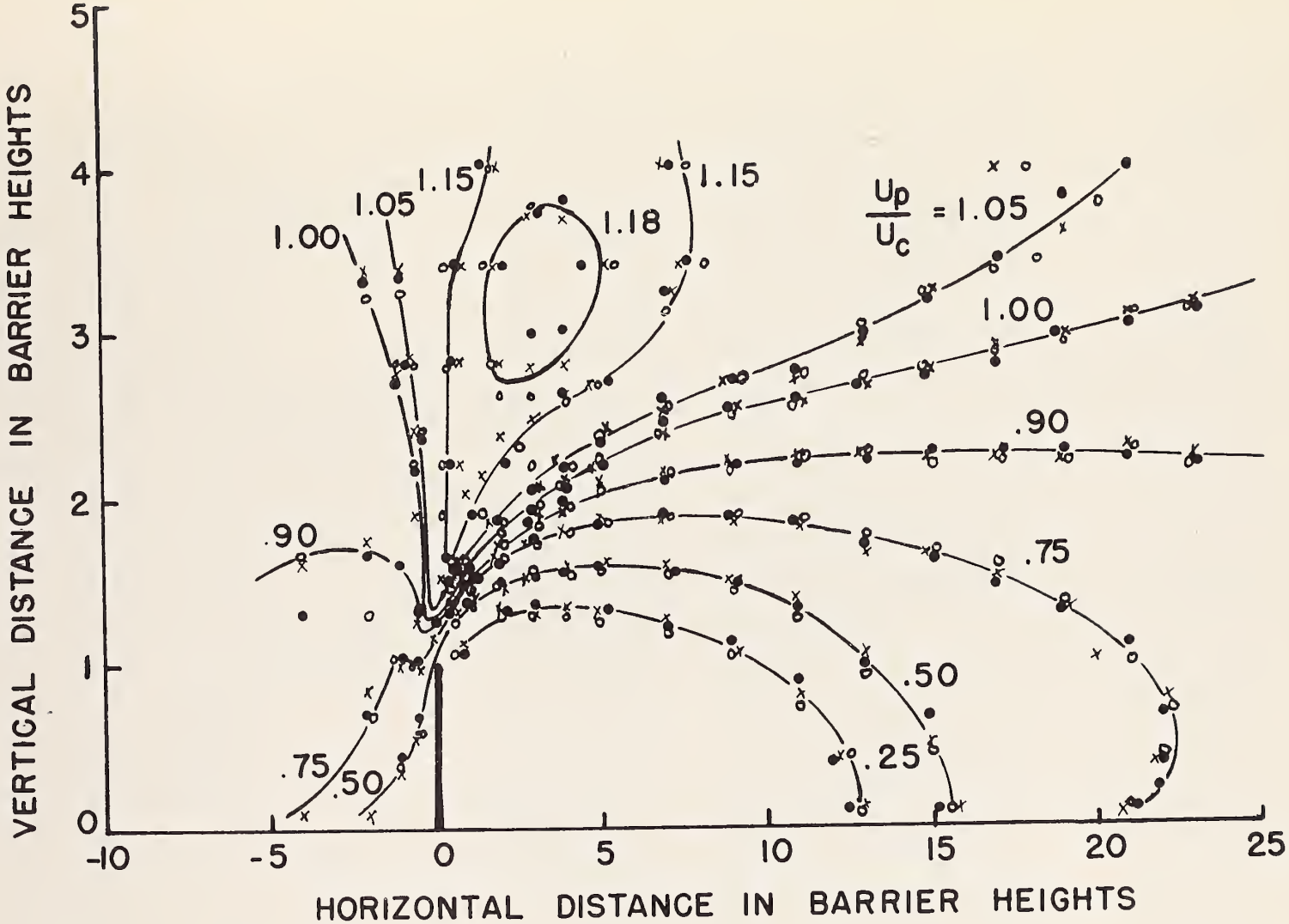

FIGURE 3.--Horizontal velocity ratios $\frac{U_p}{U_c}$ obtained in the vicinity of vertical plate for three flow velocities.

value less than the critical value for the soil: therefore, the higher the wind the less the benefit of an obstruction.

The finding in the present research that the flow pattern approaches a constant is at variance with the results of other investigators. DenUyl (9) concluded that the relative effectiveness of a windbreak decreased with an increase in velocity. On the other hand, Bates (3) concluded that, "Both the depth, expressed by percent of velocity reduction, and the width of the pool of quieted air will increase as winds become stronger, and the center will tend to move a little further away from the windbreak."

Reduction in Average Horizontal Velocity

Field measurements of velocities about a windbreak are usually made with a rotating cup anemometer or some similar device capable of measuring only the horizontal velocity. Estimates of effectiveness based on measurements made in this manner have differed widely. Bates (5) has stated that 80-percent reduction in velocity may be attained near the break, and that this will taper to insignificance at a horizontal distance of 20 times the height of the break, or 20 H. A Soil Conservation Service Bulletin (25) shows 40-percent reduction at 10 H, 25-percent reduction at 20 H, and insignificant reduction at 40 H. DenUyl (9) indicates little protection beyond 12 H and gives 40-percent reduction at 8 H for a 20-m.p.h. wind. Flensberg (10) has designated a distance reaching to 10 H as the effective zone; Barth (2) 12 H; Anderson (1) 6-15 H; Trenk (24) 50-percent reduction at 2 H; Walker (27) 80-percent at 2 H and 25 percent at 10 H; Hopkins, Palmer, and Chepil (13) say the effective zone extends to 15-30 H with 50-percent reduction at 8 H; and the Russian investigators report anywhere from 20 H to 40 H, with the predominant opinion being 25 H.

In view of the large difference in opinion as to specific effectiveness of windbreaks, it appeared desirable to make measurements of horizontal velocity reductions in the wind tunnel. It was reasoned that the range of values reported might be due to differences in shape of windbreaks evaluated. The average horizontal velocity was measured, therefore, to the leeward of each of the four previously described objects, using a constant velocity of 25 miles per hour at the 4-inch elevation. The velocity-profile maps drawn from these data are shown in figure 4, page 11. The following short table summarizes the more important results indicated in the figure.

Object	Distance at 0.1 H to:		
	75% reduction	50% reduction	25% reduction
Vertical plate	13.0 H	15.5 H	21.5 H
Triangular shape	10.5 H	15.0 H	20.5 H
Cylindrical shape	7.0 H	9.0 H	14.0 H
Model trees	(1)	13.5 H	27.0 H

[1]There is no point of 75-percent reduction at 0.1 H due to the jetting of the air through the trees.

In general, the model trees cause a more extended zone of reduction in velocity than any of the other shapes. This is evident in the 27 H distance to a 25-percent reduction and the relatively great distance between a 25-percent and a 50-percent reduction in velocity. The vertical plate reduces the velocity approximately 44 percent more than the cylinder at positions near the object and 35 percent at positions farther from the object. The plate also reduces the velocity approximately 10 percent more than does the

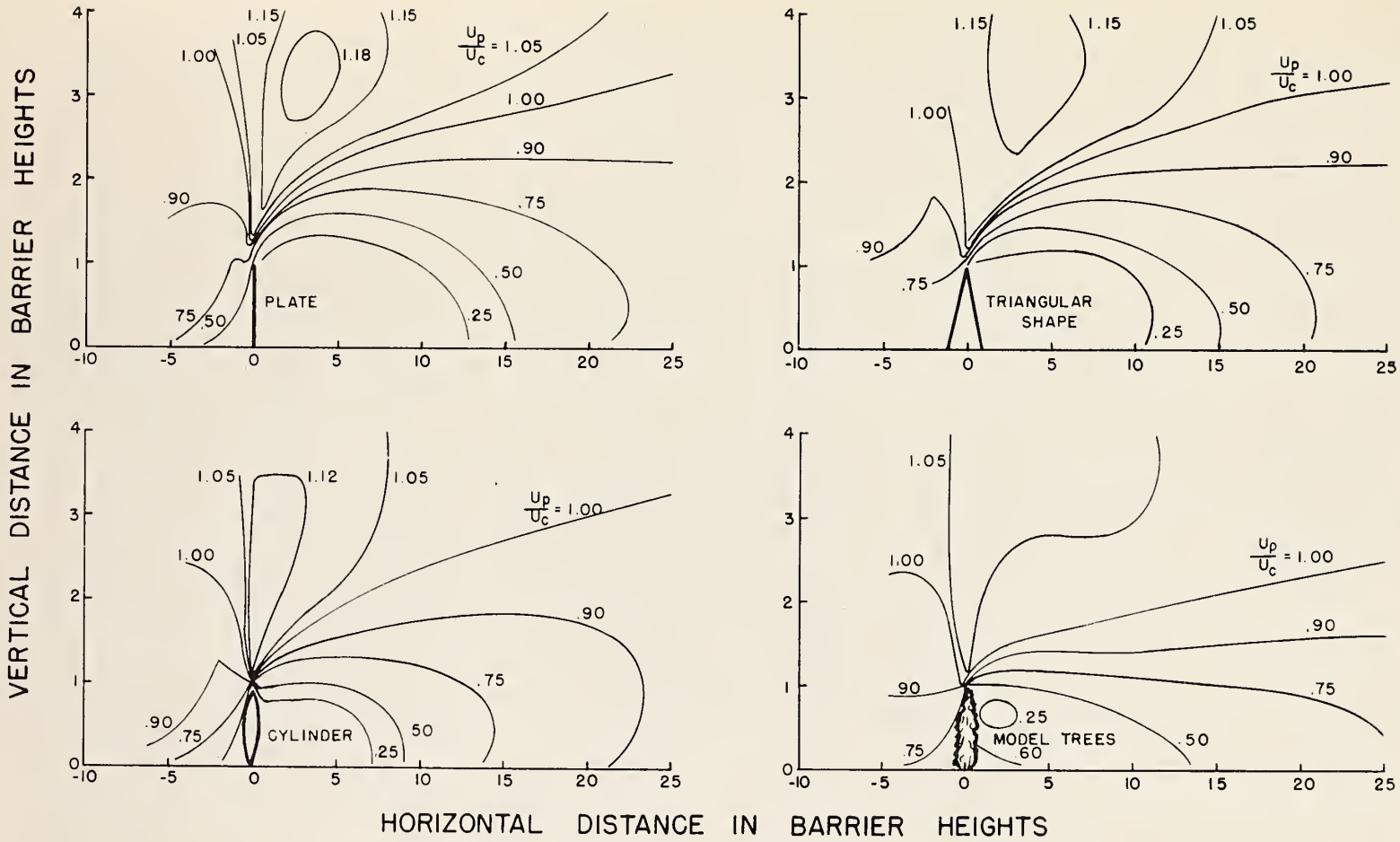

FIGURE 4.--Horizontal velocity ratios $\frac{U_p}{U_c}$ obtained in the vicinity of four barriers of varying shape.

triangular shape at both the near and far distances.

The windward reduction in velocity is relatively insignificant for all of the objects. The trees show a 20-percent reduction at -4 H; this builds up to 25 percent at -3 H, then decreases again as the air jets through the trees. The windward protection for the solid objects appears to be greatest for the triangular shape, since it is approximately -7 H to a point of 25-percent reduction. The cylinder and plate show a distance of -4 H and -4.5 H, respectively, to a 25-percent reduction, this then building up to approximately 50 percent at -2 H.

The results shown here are in reasonable agreement with field measurements made with a 50-percent solid barrier at Huron, S. Dak., (25). The distance to points of 25-percent reduction is particularly close for the cylinder or triangular shape.

Streamlines of Flow Over the Objects

As in all fields of mechanics, velocity is a vector quantity, since it possesses both magnitude and direction. The velocity vector at any point in a moving fluid generally has components in each of three coordinate directions. A Pitot tube or a cup anemometer can measure only one component of velocity, depending upon its orientation. While most field measurements have been made in this manner, they do not necessarily give a true picture of the pattern of flow about a windbreak.

In view of limitations of physical measurement in the horizontal profile, streamlines for each of the objects were determined. Since a streamline is defined as a line which lies in the direction of flow at every point, this device yields the direction and magnitude of the velocity at any point in the flow surrounding the objects.

Theory states that stream flow will follow the boundary condition throughout. It has been proved that a fluid moving with appreciable velocity will be guided by a divergent boundary only if the angle of divergence is relatively small. If this angle of divergence is large, then the phenomenon known as separation will occur at a point near the boundary with a resultant divergence upward of the streamlines. This in turn causes a large pressure drop. The resistance any boundary exerts upon the flow depends upon the components of the stresses along the boundary profile. The two stresses present are those due to viscous shear and pressure, and the resultant force is made up of a combination of the two.

Streamlining has the effect of reducing the angle of divergence with respect to the flow on the downstream side. This eases the curvature in the zone of the maximum velocity and consequently reduces the pressure drop and the eddy zone, and postpones or altogether prevents separation. In terms of the two stresses present, this means that in a streamlined boundary the forces are due almost entirely to shear or the viscous effect; whereas, in an unstreamlined boundary the viscous effects are negligible in comparison to differences in pressure fore and aft of the object. If separation occurs and a resultant force opposes motion, the magnitude of this force will vary with the shape of the body. This force is referred to as "form" drag.

Insofar as form drag is concerned it is possible to distinguish about three different types of body contour (19, p. 210): (a) that in which the point of separation is determined almost wholly by the angularity of profile, a thin plate normal to the flow being a good illustration; (b) that in which the surface curvature is appreciable, yet gradual enough for the actual point of separation to be determined in part by conditions within the boundary, the sphere being an example; and (c) that of such very easy curvature that the point of

separation occurs close to the rear, the size of the wake being reduced to a minimum as in the case of a streamlined body.

The four objects used in the experiment have elements representative of the above types of body contour. The preceding theory is applicable, therefore, in describing and clarifying the conditions of flow about the objects.

Approximate streamlines for the four objects obtained by the sketching technique are shown in figure 5, page 14. Each streamline is drawn for equal increments of flow. Since the essence of a streamline is that the rate of flow is proportional to the velocity and area between lines, zones of accelerated and retarded flow are readily discernible.

Reference to figure 5 will indicate a close agreement between theory and results in regard to divergence of streamlines. It will be noted that the topmost edge or profile of the object governs the pattern of flow. When this edge is well defined and sharp, as in the case of the plate and triangular shape, the angle of divergence is large and separation occurs with a resultant divergence upward of the streamlines. This, in turn, causes a larger and more extended turbulent wake leeward of the object. When the angle of divergence of the streamlines is greatly reduced, resulting in partial streamlining, as in the case of the cylinder, the turbulent wake is much smaller. The cylinder perhaps approaches type (b) in Rouse's (19, p. 210) interpretation of form drag since there is no doubt that separation occurs to a limited extent. The streamlines for the model trees show a lesser angle of divergence but a more extended turbulent wake leeward of the trees. This is probably due to penetration of the air through the trees. Since the turbulent wake is extended for the trees it appears that the zone of velocity reduction or lag is greater than for objects offering a solid front to the wind.

The approach of the wind to the objects appears to be practically horizontal until it reaches a point two to three heights from them. From this point it diverges upward, depending upon the degree of streamlining of the object. The direction and concentration of the streamlines immediately above and preceding the objects are of interest. It will be noted that the upward deflection is gradual and that the zone of maximum velocity is above and aft of the objects a distance of two to six times their height. Beyond this point deceleration occurs as indicated by the diverging streamlines.

Except for a slightly greater angle of deflection of the streamlines for the plate there is very little difference in the flow patterns for the plate and the triangular shape. This would indicate that the so-called hip-roof design of windbreaks may have little advantage over a single break insofar as its top profile is concerned. These data also verify Bates' (5) suspicion that, "the too wide, streamlined belt loses very largely, the benefits from the sharp upward deflection." It is realized, however, that due to certain realities, a narrow break of trees may not perform all the functions desired.

Pressure measurements made fore and aft of each object indicated a close relationship between divergence of streamlines and pressure drop. A sharp divergence upward of the streamlines, as in the case of the plate, caused a marked increase in pressure drop; whereas, in the case of the partially streamlined cylinder, the pressure drop was decreased. In terms of the two stresses present, this indicated that the largest proportion of the resistance to flow of the sharp edge profiles was due to pressure forces. In the case of the cylinder and the trees the viscous forces appeared to be of consequence.

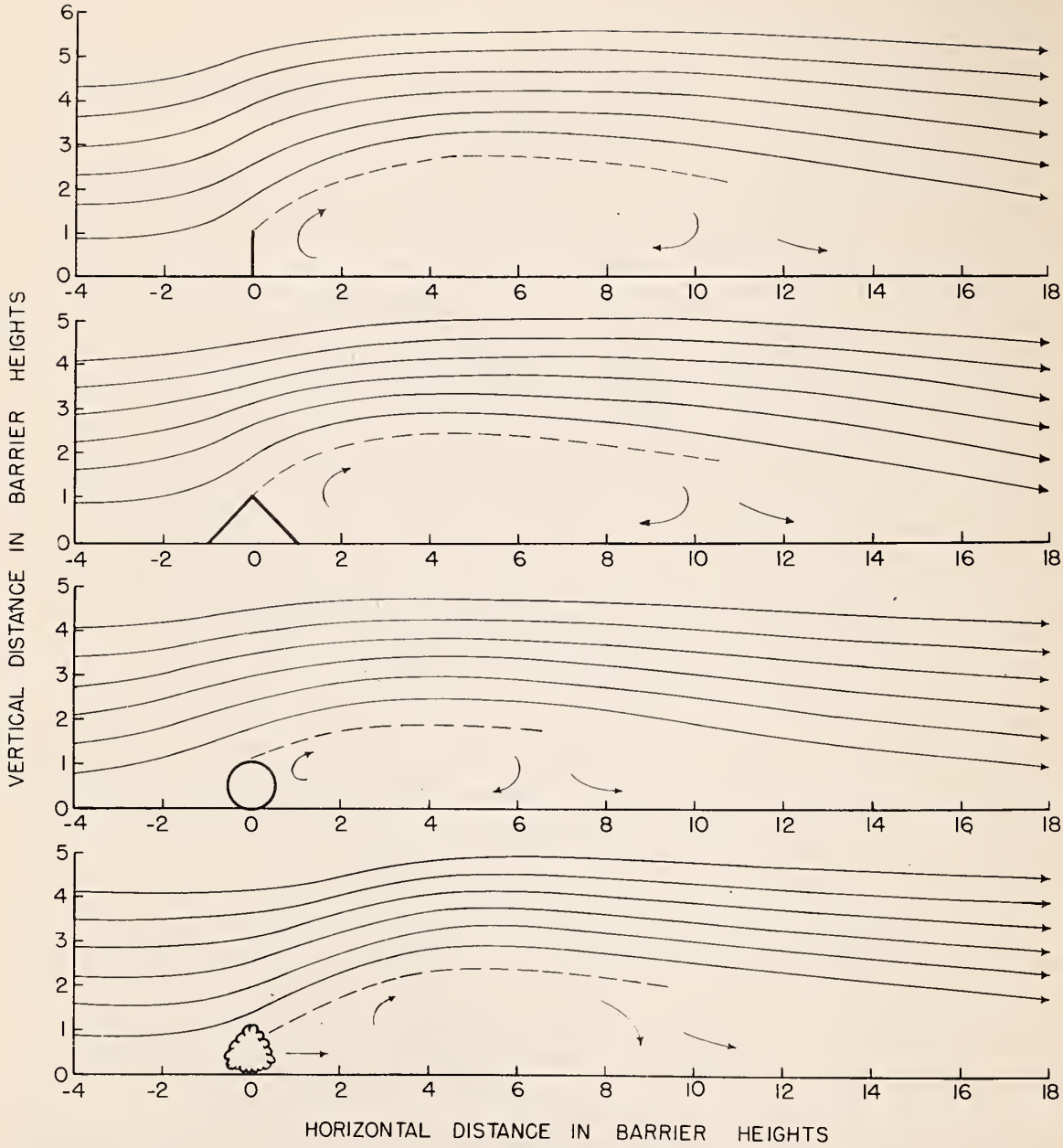

FIGURE 5.--Sketches showing approximate streamlines of flow around barriers of varying shape. The dotted curve represents the approximate surface of separation to the lee of the object.

Force and Velocity on the Surface to the Lee of the Objects

There are limitations to the zone in which streamlines may be used. These limitations stem from the fact that a streamline cannot be determined in the turbulent wake of the object, nor in the boundary layer near the surface. It was found physically impossible to describe this flow in the ordinary manner. For this reason the method of shear patterns described previously was used.

The method of shear patterns is based on the concept that a velocity ratio $\frac{u}{u_o}$ may be related to levels of shear as follows:

$$\frac{u}{u_o} = \sqrt{\frac{\tau}{\tau_o}} \tag{2}$$

where u_o is the threshold velocity for a given erodible material in a clear tunnel, u is a velocity of known magnitude greater than the threshold also measured in a clear tunnel, τ_o is the threshold shear, and τ is a shear of known magnitude greater than the threshold.

Experiments were conducted using each of the four objects. A graded dune sand, 0.30-0.42 mm. in size, was used as the vehicle for establishing the patterns. Four levels of wind, each yielding values of $\frac{u}{u_o} > 1$, were passed over the objects and the sand. The boundary of the sand pattern remaining at the end of each test denoted the location at which the barrier reduced the shear at the bed level to τ_o. This is the equivalent of reducing the value of $\frac{u}{u_o}$ to unity at the same location. This reduction in $\frac{u}{u_o}$ will be termed the effective velocity reduction. Expressed as a percent it is:

$$\text{Effective Percent Reduction} = \frac{100\left(\frac{u}{u_o} - 1\right)}{\frac{u}{u_o}} \tag{3}$$

Figure 6, page 16, presents dimensionless curves obtained from the experiment. The curves indicate the effective percent reduction to the lee of a given object irrespective of the velocity of the wind. It is evident that the percent reduction in velocity at the surface to the leeward of each object varies in an irregular manner with length. If the curves are extrapolated, two zones of maximum velocity reduction may be established. These zones may be designated as "A" and "B." Zone "A" is located immediately aft of the objects; zone "B" ranges in location from 6 to 11 times the height of the various objects.

The minimum reduction between zones "A" and "B" occurs at a distance equal to two to eight times the height of the objects. Beyond zone "B" the effective percent reduction decreases and approaches zero at 37 to 52 H. The effective reduction in the

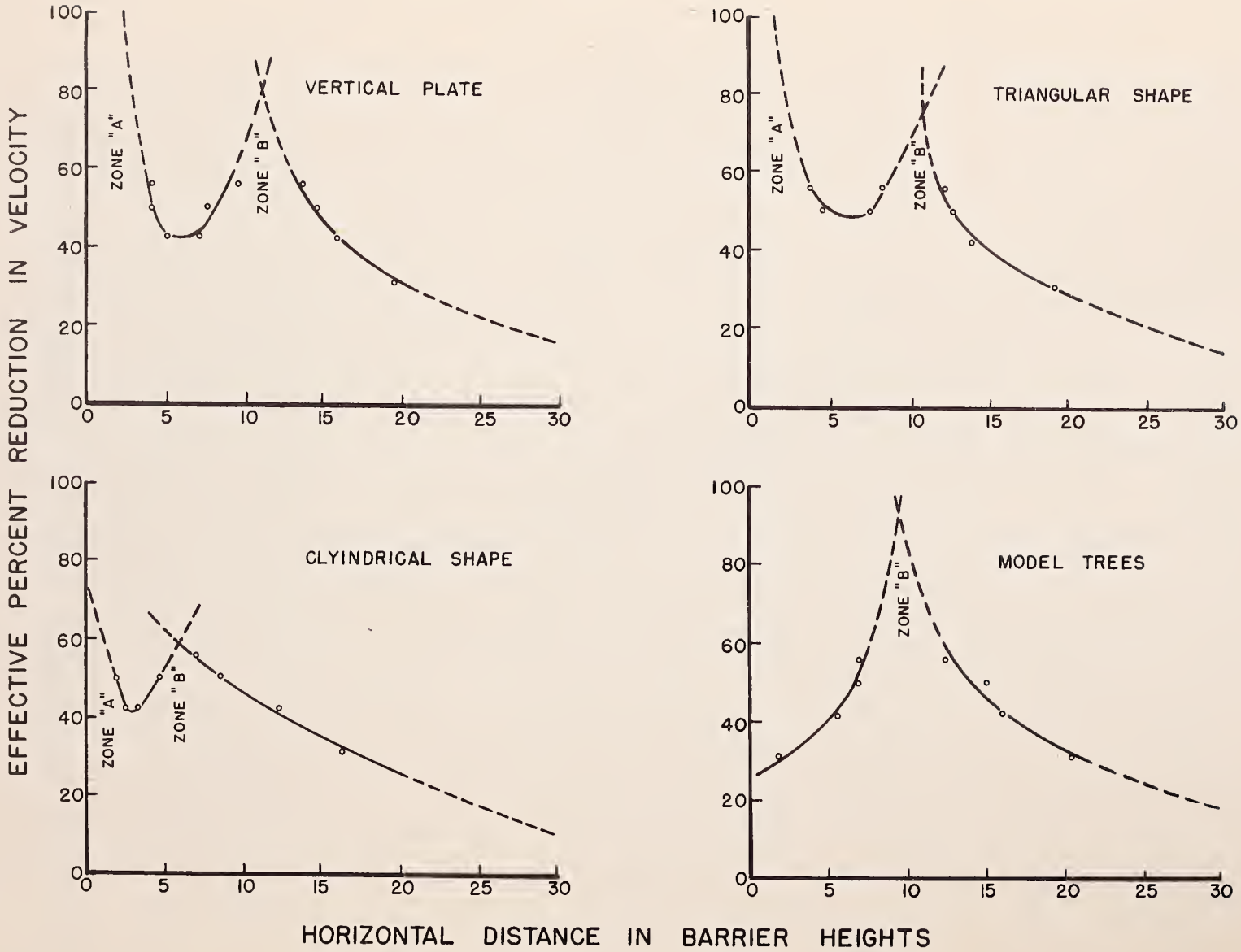

FIGURE 6.--Dimensionless curves showing effective velocity reductions at the bed level to the lee of barriers. Values obtained from erosion patterns in sand placed on floor of wind tunnel.

zone between 2 and 8 H will not eliminate sand movement when $\frac{u}{u_o}$ exceeds a limiting value. Observation showed that the flow in this region was very turbulent, moving in all directions in general and toward the object in particular. When the limiting value of $\frac{u}{u_o}$ was exceeded, this reverse flow caused drifting and ripples near the objects. Of the three solid barriers, the triangular shape showed the least development of this turbulent flow near the object. It will be noted from figure 6, page 16, that the curve representing the condition in proximity to the trees is not U-shaped. This is due to the jetting of air between the trees.

Net zones of velocity lag of known effective percent reduction at the bed level may be determined from the curves of figure 6. The area under the curves for a given barrier will yield an "index of protection" similar to Bates' (5) units of wind reduction. A summary of pertinent data from figure 6 is given in table 1, page 18.

From table 1 it will be noted that a reduction equal to 100 percent in effective velocity occurs in zone "A" for short distances to the lee of the plate and triangular-shape barriers. In zone "B" the extrapolations of values indicate that the model trees attain the maximum percent reduction in velocity. This distance and percent reduction in velocity is at least for the cylindrical shape. The apparent limit of the zone of influence is greatest for the trees and least for the cylindrical shape. The net effective zone where the velocity is reduced to 50 percent is greatest for the vertical plate. For reductions of 25 percent the net zone is greatest for the model trees. The over-all picture given by the values of the "index of protection" shows the objects ranking in the order: vertical plate, triangular shape, model trees, and cylindrical shape.

It is evident that porosity and shape are items which may well be considered in designing barriers or windbreaks. Their design would be dependent somewhat on the levels of wind movement for a given region. If winds were relatively low, a 25-percent reduction might be sufficient to accomplish a given objective; however, if periods of extremely high winds were encountered frequently a 50-percent reduction would possibly be required. Porous versus sharp-profiled obstructions could be adapted to these two contrasting conditions.

A comparison of the method of shear patterns and the method of horizontal velocity measurements shows that the two approaches give comparable results for an effective zone classified as that having a 25-percent reduction in velocity. At the 50-percent effective reduction level, the net zone at the surface is reduced 25 to 30 percent below that indicated by horizontal measurements at 0.1 H. These results appear reasonable, since the streamlines of flow show a very turbulent wake near the object where the 50-percent reduction zone is located. The horizontal component of velocity in this zone accounts for only a portion of the actual force at the surface.

The method of shear patterns was also used to study the area of protection of a barrier in relation to its length and to clarify the effects of jetting of wind through a porous barrier. Separate experiments were conducted for each of these studies.

Five 1-inch solid barriers, having lengths of 6 H, 12 H, 18 H, 24 H, and 30 H were used in the study of length and area protected. The barriers were placed in the tunnel at 90-,45-,and 30-degree angles to the wind. In a constant wind equal to 1.25 u_o it was found that the area was parabolic in shape regardless of the angle of approach of the

TABLE 1.--*Summary of velocity reduction, apparent zones of influence, net effective zones of velocity lag, and indexes of protection from figure 6*

Object	Effective velocity reductions and distances to lee of objects			Apparent limit of zone of influence	Net effective zones of velocity lag		Index of protection (Area under curve)
	Zone A	Zone B					
	Range of 100% reduction	Distance	Reduction		50% reduction Distance	25% reduction Distance	
	H units	*H units*	*Percent*	*H units*	*H units*	*H units*	
Vertical plate	0-2.50	10.7	83	49	10.2	23.5	15.0
Triangular shape	0-1.25	10.5	76	46	9.5	22.5	14.4
Cylindrical shape	[1]0	6.7	59	37	6.0	20.5	10.9
Model trees	[2]0	9.5	94	52	7.5	25.0	13.7

[1]Maximum equals 74 percent reduction at surface of cylinder.
[2]94 percent is maximum attained, due to jet effect.

wind. The data obtained from the experiment further showed the area to be proportional to the square of the length of the barrier normal to the wind for values up to approximately 20 H. Beyond this limit the area appears to be directly proportional to length.

The results of the jet-effect studies, wherein the model trees were used, are shown by photograph in figure 7, page 20. While the area affected is not large it is evident that a problem of erosion adjacent to a porous barrier does exist. It should not be concluded, however, that this penetration should be eliminated. On the contrary, reference to the streamlines and shear patterns of the solid objects and the trees will show that if the goal for effectiveness is not set too high the trees are superior to the solid objects.

Extension of Results to Atmospheric Conditions

In view of the general agreement of wind-tunnel results with reported field measurements it seems advisable to extend these results to atmospheric conditions. While the results using all shapes could be used in such an analysis, the model trees will be used as an example since they are more nearly representative of windbreaks used in the field.

The Reynolds number of the experiments, using the 4-inch model trees and a velocity of 25 miles per hour is $7.56(10^4)$. The Reynolds number for full-scale 30-foot trees in a wind velocity of 25 miles per hour will be $6.87(10^6)$. However, since the pattern of flow around similar barriers presumably approaches a constant for Reynolds numbers of this order, values obtained in the wind tunnel should approximate field conditions.

The method by which the placement of a windbreak in the open may be evaluated can be illustrated by use of a simplified hypothetical problem as follows:

Problem: A 30-foot windbreak having geometric similarity to the model trees used in the wind tunnel is placed in the field. The ground surface is composed of sand averaging 0.25 mm. in diameter. Assume that a windstorm of 2-year recurrence frequency during the month of April blows normal to the break. What are some of the conditions of protection to the lee of the windbreak?

Information Required: The threshold velocity, u_o, for a 0.25 mm. dune sand is approximately 14 miles per hour as measured at a 2-foot height in the field. According to Zingg (28) the expected level of wind movement in the High Plains for April is 26 miles per hour as an average for a 3-hour period. This figure is the maximum expected to occur at 2-year intervals at a 2-foot height above the ground. The dimensionless graph of figure 8, page 21, shows the relationship between $\frac{u}{u_o}$ and distances from the barrier at which velocities will be reduced to an effective value $\leqq u_o$. A graph of this type is necessary for the solution of the problem.

Solution: Assuming the average wind velocity for the 3-hour period to be constant at 26 miles per hour, the value of $\frac{u}{u_o} = \frac{26 \text{ mph}}{14 \text{ mph}} = 1.86$. Referring to figure 8, it will be found

FIGURE 7.--Pattern of sand removal to the leeward of model trees, as seen from above.

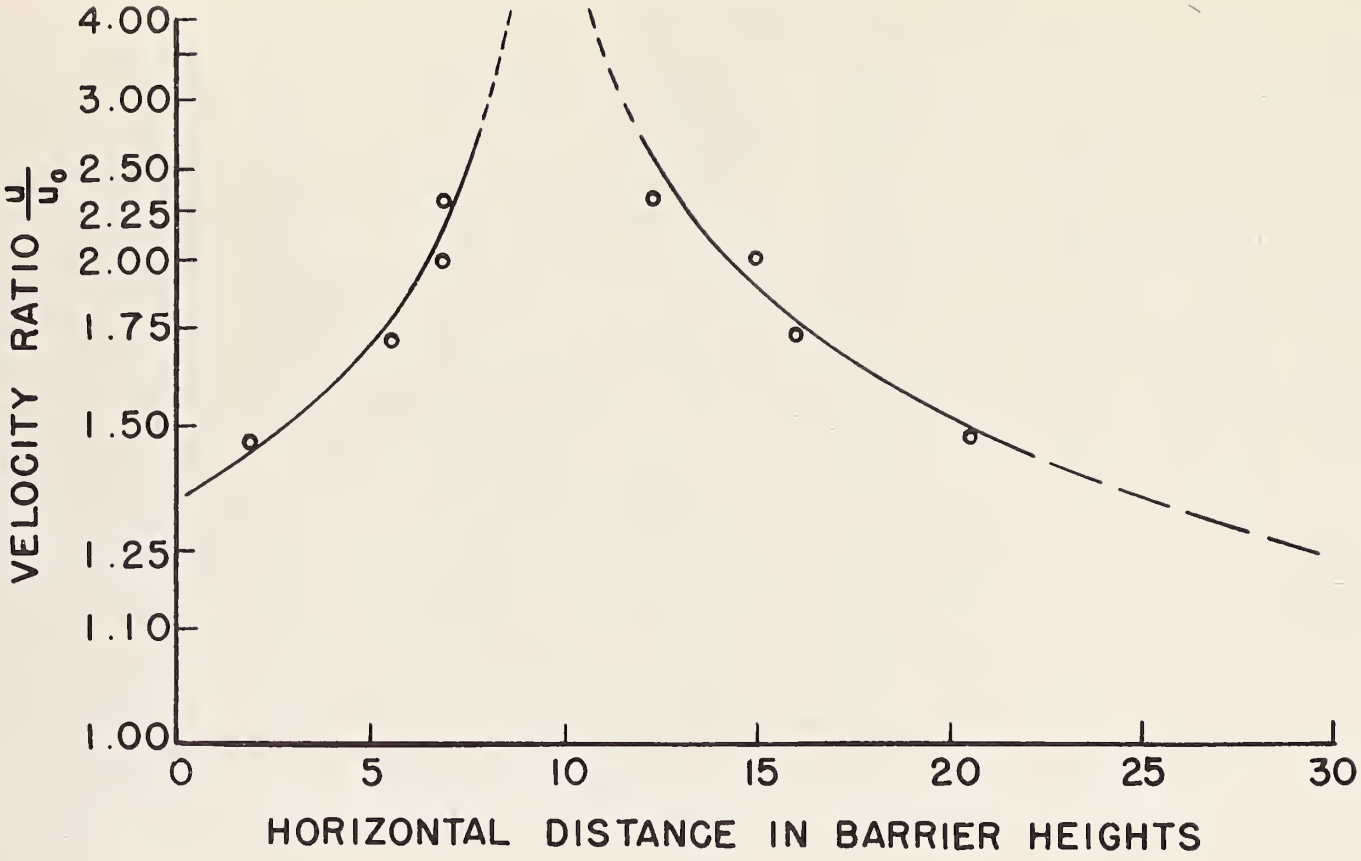

FIGURE 8.--Curves showing horizontal distances to lee of model trees at which winds of given velocity ratios $\frac{u}{u_o}$ are reduced to an effective value of u_o at the bed level.

that the indicated limits of complete protection for a value of $\frac{u}{u_o} = 1.86$ lie between 6- and 15-barrier heights, or a net distance of 9-tree heights. This is a horizontal distance of 270 feet starting 180 feet away from the 30-foot trees. Thus the porosity of the break would permit erosion to occur in a zone adjacent to the barrier. It will be noted from figure 8, page 21, that some degree of protection less than that required to control drifting would accrue throughout the entire zone of influence of the windbreak. This simplified solution does not take into account the fluctuations of wind velocity which would occur in a 3-hour wind. Suffice to state that they would vary greatly about the average value of 26 miles per hour, and the zone of more or less complete protection and the level of partial protection in the total zone of influence would be a variable.

DISCUSSION

Several phases of the windbreak problem have been considered in this investigation. There are, however, certain characteristics of the problem which are not completely amenable to solution by use of the wind tunnel at the present time. It is the purpose of this section to discuss some of these characteristics and limitations.

For the most part results have been in favorable agreement with field measurements reported by other investigators. Discrepancies have arisen, however, in regard to flow patterns. This study has indicated that the flow pattern tends to remain constant irrespective of the level of the wind. Other investigators have concluded that the flow pattern is not constant. DenUyl (9) found that the flow pattern was modified to yield relatively less protection with increasing levels of wind velocity. Others (3, 13) have shown the flow pattern to change in such a manner that the relative benefit of the barrier is increased as the wind velocity becomes higher. It is possible that the factors of porosity and the basic differences in flow characteristics under controlled wind-tunnel conditions and atmospheric conditions may enter into this phenomenon. Again, a break in the near-constant value of the drag coefficient C_d occurs for flow about some objects at a Reynolds number between 10^5 and 10^6. This phenomenon may have a bearing on the problem. In any case, the results indicate the need for additional corroborative field investigations.

The analysis of flow about the barriers has been restricted to flow having velocity components in only two of the three coordinate directions. While the flow is basically two-dimensional in the wind tunnel, it may or may not be so under a fluctuating, turbulent atmospheric condition.

The influences of multiple windbreaks have not been considered in this study. There are two reasons for this: (a) The problems relating to a single windbreak offer a challenge in themselves, and (b) the complexity of the multiple windbreak problem is such that the interpretation of wind-tunnel results to atmospheric conditions is difficult. It is believed that the solution to this problem should come partially through the evaluation of artificial barriers under atmospheric conditions.

While the extension of the wind-tunnel results to atmospheric conditions appears to give reasonable results, it is realized that the approach is speculative and depends for its validity upon the applicability of the Reynolds parameter. Some investigators are of

the opinion that the Reynolds number cannot be applied in a straight-forward manner to the atmosphere. The Reynolds number analysis is based upon a zero lapse rate, whereas under atmospheric conditions the lapse rate is variable. This serves to add the additional complexity of turbulence due to the lapse rate of temperature. Most wind-tunnel results in the past, however, have used this parameter as a means of extending the results, and until more information is obtained it appears to be the best tool for the operation.

This investigation is not intended as the final answer to all of the aerodynamic problems associated with windbreaks. It is believed, however, that the results throw some light on a complex problem which is plagued with many conflicting answers.

SUMMARY

Wind-tunnel tests were conducted to obtain fundamental information on problems related to windbreaks.

Three known geometrical shapes of barriers and a model tree windbreak were utilized to evaluate the effect of shape on flow patterns. Wind-tunnel data are presented on the effect of barrier shape on flow patterns, similarity of flow patterns, and the zone of influence of single barriers of different shape. These results are also extended to atmospheric conditions. Pitot-tube measurements of horizontal velocity, velocity-profile maps, streamlines of flow, and shear patterns are employed to describe the flow about the objects.

The resistance to flow around a given object was found to be independent of the Reynolds number at the relatively high ranges of the number used. Flow patterns were also found to be similar irrespective of the level of velocity. Thus, a constant percent reduction in velocity at a given location irrespective of the level of wind is indicated. The absolute protection is, however, dependent on the level of the wind.

It was found that the object's value in protecting the area to the leeward depended somewhat upon the requirements set for effectiveness. The objects listed in order of their effectiveness in creating a velocity of reduction $\geqq 50$ percent are: the plate, the triangular shape, the trees, and the cylinder. The objects listed in order of their effectiveness in creating a velocity reduction $\geqq 25$ percent are: the model trees, the plate, the triangular shape, and the cylinder. It was concluded from these results that density and shape are factors which should be considered in the design of a windbreak. The employment of these factors in the design would depend somewhat on the velocity of wind movement for the region.

The streamlines of flow follow a gradual contour over each of the objects with no abrupt change in direction indicated. The zone of maximum velocity was found to be above and aft of the objects a horizontal distance equal to two to six times the height.

Flow patterns and effective velocity reductions for the vertical plate and the triangular shape were nearly comparable; this indicates that a "ship-roof" windbreak design may have little advantage over other possible arrangements.

A method of shear patterns was used to describe the conditions at the surface to the lee of a given object. It was shown that the effective percent reduction in velocity at the surface varies in an irregular manner with length. Trend curves of percent velocity reduction with length indicate two zones of maximum and two zones of minimum reduction for solid barriers, and one zone of maximum and two zones of minimum reduction for the

porous trees. This method also showed that windbreak effectiveness based on horizontal velocity measurements may be 25 to 30 percent in error in the zone immediately aft of the barrier.

The studies indicated that the areas of protection aft of the barriers vary as the square of the length of the break normal to the wind for values up to approximately 20 H. It was further indicated that this area is parabolic in shape regardless of the angle of approach of the wind.

A simple hypothetical problem was used to illustrate the extension of the results to atmospheric conditions. The required information for solution of the problem is duration and recurrence-interval data for winds and the threshold velocity of the soil for a given location.

LITERATURE CITED

(1) Anderson, R. H.
1931. TREE PLANTING ON THE FARM. New South Wales Dept. Agr. Farmers' Bul. 167, p. 7.

(2) Barth, A.
EFFECT OF WIND IN CAUSING DECREASE IN FOREST YIELDS AND MEANS OF COUNTERACTING IT. (Translated from the Swedish by C. Mygind, Div. of Sil., U. S. Forest Service. 1934. Mimeo. p. 26).

(3) Bates, C. G.
1930. THE WINDBREAK AS A FARM ASSET. U. S. Dept. Agr. Forest Serv. Bul. 1405 (revised).

(4) _____
1911. WINDBREAKS: THEIR INFLUENCE AND VALUE. U. S. Dept. Agr. Forest Serv. Bul. 86, p. 45.

(5) _____
1945. SHELTERBELT INFLUENCES: PART I GENERAL DESCRIPTION OF STUDIES MADE, pp. 88-92; PART II THE VALUE OF SHELTERBELTS IN HOUSE HEATING, pp. 176-196. Jour. Forestry 43.

(6) Chepil, W. S.
1949. WIND EROSION CONTROL WITH SHELTERBELTS IN NORTH CHINA. Amer. Soc. Agron. Jour. 41: 127.

(7) Cheyney, E. G.
1941. ESTABLISHMENT, GROWTH, AND INFLUENCE OF SHELTERBELTS IN THE PRAIRIE REGION OF MINNESOTA. Minn. Agr. Expt. Sta. Bul. 285.

(8) Clark, E. A.
1934. A PRELIMINARY REPORT ON THE GROWTH AND EFFECTIVENESS OF WINDBREAKS IN THE HIGH PLAINS AREA OF OKLAHOMA. Panhandle Bul.55. Goodwell, Okla.

(9) DenUyl, D.
1936. THE ZONE OF EFFECTIVE WINDBREAK INFLUENCE. Jour. Forestry 34: 689.

(10) Flensborg, C. E.
HEDGE AND SHELTER PLANTING. (Translated from Danish by H. Ronn, Div. of Sil. U. S. Forest Serv. 1934. Mimeo. p. 2)

(11) George, E. J.
1948. SPACING DISTANCE FOR WINDBREAK TREES ON THE NORTHERN GREAT PLAINS. U. S. Dept. Agr. Circ. 770.

(12) Goviadin, Z.
FOREST IN THE SERVICE OF AGRICULTURE. (U. S. Dept. Agr. Mimeo. Bul. Trans. from Russian. 1933.)

(13) Hopkins, E. S., Palmer, A. E., and Chepil, W. S.
1946. SOIL DRIFTING CONTROL IN THE PRAIRIE PROVINCES. Canada Dept. Agr. Farmers' Bul. 32 (revised).

(14) Hood, G. W.
1938. WINDBREAKS HELP CONTROL EROSION IN GREAT PLAINS. Soil Conserv. III: 247.

(15) Leontiensky, N. P.
THE PLANS OF SHELTERBELT PLANTINGS IN RAISING THE AGRICULTURAL YIELD. (Translated from the Russian. U. S. Dept. Agr. Mimeo. Bul. 1934.)

(16) Malina, F. J.
1941. RECENT DEVELOPMENTS IN THE DYNAMICS OF WIND-EROSION. Amer. Geophys. Union Trans. p. 279.

(17) Moreland, W. N.
1950. INFLUENCE OF SHELTERBELTS ON ADJACENT CROPS. A Master's Report, Horticulture Dept., Kans. State Col.

(18) Ross, N. M.
1936. ROLL OF TREES IN MODIFYING AGRICULTURE OF THE DRY AREAS OF THE PRAIRIE PROVINCES. Sci. Agr. 16: 266-269.

(19) Rouse, H.
1938. FLUID MECHANICS FOR HYDRAULIC ENGINEERS. McGraw-Hill Book Co., Inc. New York.

(20) ———
1950. ENGINEERING HYDRAULICS. John Wiley & Sons. New York. pp. 1-115.

(21) Russell, G. E.
1948. HYDRAULICS. Henry Holt & Co. New York. pp. 122-124.

(22) Soos, N. I.
FOREST MELIORATION AND EFFECTS TO COMBAT DROUGHT IN SOUTHEASTERN RUSSIA. (Translated from Russian by C. S. Prodan. 1926.)

(23) Stoeckeler, J. H.
1938. SHELTERBELT PLANTING REDUCES WIND EROSION DAMAGE IN WESTERN OKLAHOMA. Amer. Soc. Agron. Jour. 39: 923-931.

(24) Trenk, F. B.
1948. INFLUENCE OF PLANTED TREE BELTS IN PLAINFIELD SAND ON EROSION CONTROL AND MOISTURE CONSERVATION. Iowa State Col. Jour. Sci. 22: 449.

(25) U. S. Soil Conservation Service.
1947. TREE WINDBREAKS FOR THE SOUTHERN PLAINS. Regional Forestry Div., Western Gulf Region. Mimeo. Bul.

(26) Vyssotsky, G. N.
1935. SHELTERBELTS IN THE STEPPES OF RUSSIA. Kharkov, Ukraine, U. S. S. R. Jour. Forestry 33: 781.

(27) Walker, J.
1946. PLANNING AND PLANTING FIELD SHELTERBELTS. Canada Dept. Agr. Farmers' Bul. 139.

(28) Zingg, A. W.
1950. THE INTENSITY-FREQUENCY OF KANSAS WINDS. U. S. Soil Conserv. Serv. Tech. Pub. 88. p. 19.

(29) ———
1951. SOME CHARACTERISTICS OF AEOLIAN SAND MOVEMENT BY THE SALTATION PROCESS. Paper presented at the aeolian wind action conference, Algiers, Algeria. March 27-31.

(30) ———, and Chepil, W. S.
1950. AERODYNAMICS OF WIND EROSION. Agr. Engin. 31: 279-282, 284.